Nanotechnology: From Imagination to Reality

Imagine a single area of scientific discovery with the potential to enable a wealth of innovative new technologies across a vast array of fields including healthcare, information technology, energy production and utilization, homeland security and national defense, biotechnology, food and agriculture, aerospace, manufacturing, and environmental improvement. Nanoscience, the study of the unique properties of matter that occur at extremely small scales, has this potential.

Advances in nanoscience and nanoengineering are already ushering in new applications—or nanotechnologies—that are leading to improved products across a broad realm of sectors, from textiles to electronics. Some of these improved products are already available, including improved catalysts, stain resistant fabrics, better sunscreens, superior dental bonding materials, high resolution printer inks, digital camera displays, and high capacity computer hard disks, to name a few.

In addition to making existing products and processes better, nanotechnology promises breakthroughs that will revolutionize the way we detect and treat disease, monitor and protect the environment, produce and store energy, and build complex structures as small as an electronic circuit or as large as an airplane. For example, microscopic devices small enough to be carried in the human bloodstream may someday monitor the body for early signs of disease and deliver treatments that are targeted to the appropriate cells of the body. Exquisitely sensitive and selective sensors could be deployed in uses ranging from environmental stewardship to food safety to homeland security. And materials with superior characteristics—many times stronger than steel but a fraction of its weight, for example—could be used to build better cars, planes, spacecraft, buildings, and creations we have yet to imagine. Clearly, nanotechnology has the potential to profoundly change our economy, to improve our standard of living, and to bring about the next industrial revolution.

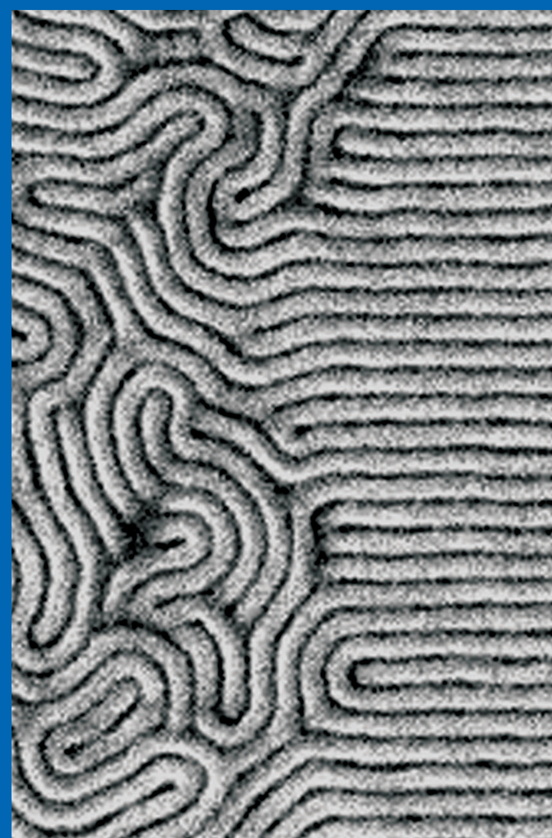


Figure 1. Scanning electron-microscope image of top edges of thin sheets of polystyrene and polymethyl-meth-acrylayte. The ordered arrangement of the stripes , each about 24 nm wide, on the right was generated by a striped nano-pattern on the substrate surface. The left part of the substrate was unpatterned (courtesy P.F. Nealey and S.O. Kim, University of Wisconsin).

The scientific discoveries that will enable these breakthroughs entail more than simply the miniaturization of existing technologies. Nanoscale science, engineering, and technology, collectively referred to as nanotechnology, define research and development (R&D) aimed at understanding and working with—seeing, measuring, and manipulating—matter at the atomic, molecular, and

Recent achievements in nanotechnology funded in whole or in part by the National Nanotechnology Initiative

- Use of the bright fluorescence of semiconductor nanocrystals (quantum dots) for dynamic angiography in capillaries hundreds of micrometers below the skin of living mice—about twice the depth of conventional angiographic materials and obtained with one-fifth the irradiation power.
- Nano-electro-mechanical sensors that can detect and identify a single molecule of a chemical warfare agent—an essential step toward realizing practical field sensors.
- Nanotube-based fibers requiring three times the energy-to-break of the strongest silk fibers and 15 times that of Kevlar fiber.
- Nanocomposite energetic materials for propellants and explosives that have over twice the energy output of typical high explosives.
- Prototype data storage devices based on molecular electronics with data densities over 100 times that of today's highest density commercial devices.
- Field demonstration that iron nanoparticles can remove up to 96% of a major contaminant (trichloroethylene) from groundwater at an industrial site.

supramolecular levels. This correlates to length scales of roughly 1 to 100 nanometers. At this scale, the physical, chemical, and biological properties of materials differ fundamentally and often unexpectedly from those of the corresponding bulk material. Nanotechnology R&D is directed toward understanding and creating improved materials, devices, and systems that exploit these fundamentally new properties, phenomena, and functions. An example of the type of nanoscale structures that can be grown by highly controlled fabrication processes is shown in Figure 1.

With any new and disruptive technology, and particularly one that has significant potential for extremely broad impact, there will be societal and ethical implications. Understanding these implications and ensuring that their consideration is integrated with the development of the technology is vital to achieving the maximum societal benefit. The Federal R&D program includes societal and ethical implications as one of its principal elements.

In order to coordinate the multiagency Federal R&D program in nanotechnology, the National Nanotechnology Initiative (NNI) was established in FY 2001. The goals of the NNI are to: (1) conduct R&D to realize the full potential of this revolutionary technology; (2) develop the skilled workforce and supporting infrastructure needed to advance R&D; (3) better understand the social, ethical, health, and environmental implications of the technology; and, (4) facilitate transfer of the new technologies into commercial products.

The National Nanotechnology Initiative: Fueling Innovation...

... By Improving Fundamental Understanding

The state of nanotechnology today represents something of a paradox. On the one hand, new products using nanotechnology have been developed and are in the marketplace. On the other hand, understanding of the underlying properties of nanoscale materials and structures is still at a rudimentary level. Many existing models for explaining material, device, and system behavior do not extrapolate to the nanoscale regime. In order to maximize the development of future innovations, a significant portion of the NNI investment is directed toward basic research to achieve a fundamental understanding of nanoscale properties and processes.

Basic research, even when aimed at a specific problem, can lead to surprising new results. Such surprises frequently are the bases for the most innovative technological advances. Therefore, a broad-based, balanced, knowledge-oriented research investment is crucial not only to advancing the frontiers of science, but also to realizing the full economic potential of nanotechnology. The surprising discoveries and new research tools that result from investment in nanotechnology research will undoubtedly have far-reaching impacts in other fields of science and engineering as well. Many agencies such as NSF and DOE have a focus on support for fundamental research.

As it has in the past in areas such as information technology and biotechnology, investing in basic research in nanotechnology is expected to lead to significant, new economically valuable technologies. However, the time to take a concept developed through basic nanotechnology research to a commercial product is beyond five or even ten years—or, for truly fundamental research, may be altogether unknown. Therefore, private investors are not generally in a position to provide the necessary financial support. Because nanotechnology is of such critical import to U.S. competitiveness, both economically and technologically, even at this early stage of development, it is a top priority within the Administration's R&D agenda.

... By Focusing on Applications

A broad, balanced basic research program both complements and supports more focused work aimed at incorporating scientific discoveries into innovative technologies. Many agencies such as DOD, DOE, EPA, NASA, NIH, NIST, and USDA support applied research aimed at developing technology related to the agency's mission. Federal investment in a combination of fundamental and applied research will move novel concepts closer to applications that are useful for both government and commercial purposes.

... Through Multidisciplinary Collaborations

Another aspect of nanotechnology R&D worth noting is the key role played by multidisciplinary and interdisciplinary efforts. That is, advances will be built upon progress in more than one area of research or on truly collaborative interactions among researchers from various disciplines. A key component of the NNI is coordination of the Federal investment and strengthening of intra- and interagency efforts fostering multidisciplinary research.

... By Facilitating Technology Transfer

At this early stage, an important mechanism by which nanotechnology can find its way into commercial applications is through interaction among industry, academic, and government researchers. Such networking and partnering is facilitated and encouraged under the NNI by the establishment or support of centers, networks, and facilities that are available to researchers from all sectors. Examples include the existing National Nanofabrication Users Network (NNUN) and a suite of Nanoscale Science Research Centers (NSRCs), each with a specific focus, to be colocated at Federal laboratories across the country. Interaction among researchers from various sectors is also facilitated under the NNI through the organization of topical workshops.

Additionally, small businesses, which are frequently at the forefront of the development of new, high technology products, can receive support through the agency-run Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs directed specifically at nanotechnology-based solutions. A goal of all of these efforts is to expedite knowledge transfer and, ultimately, to facilitate commercialization of nanotechnology. By addressing measurements, standards, and manufacturing directly in the grand challenges, the NNI is ensuring that the appropriate infrastructure is developed to facilitate the rapid commercialization of laboratory successes.

... For Enhanced U.S. Competitiveness

The United States is not the only nation to recognize the tremendous economic potential of nanotechnology. While difficult to accurately measure, some have estimated that worldwide government funding has increased to about five times what it was in 1997, exceeding $2 billion in 2002.[1] In the United States, the Federal investment in nanotechnology R&D has increased from $116 million in FY 1997[2] to a request of $849 million in FY 2004. In order to realize nanotechnology's full potential and to maintain a competitive position in the worldwide nanotechnology marketplace, the Federal Government's investment will continue to play a critical role in accelerating scientific discovery and nurturing new technologies and fledgling industries.

... Responsibly

Since the inception of the NNI, assessing the implications of the technology has been an integral part of the planning and programs of the Initiative. Research on implications for human health, society, and the environment is increasingly being emphasized as tangible new nanostructures and nanomaterials are discovered and new nanotechnology products are developed. The results of such research are being taken into consideration by those Federal agencies whose work is directed at regulatory issues.

[1]M.C. Roco. 2002. "International Strategy for Nanotechnology Research and Development," *Journal of Nanoparticle Research,* Kluwer Academic Publishers, Vol. 3, No. 5-6, 2001, pp. 353-360, as updated April 5, 2002: http://nano.gov/intpersp_roco.html.

[2]R.W. Siegel et al. 1999. *Nanostructure Science and Technology,* Kluwer Academic Publishers, Chapter 8, p. 133: http://www.wtec.org/loyola/nano/08_01.htm.

NNI Program Overview: Interagency Coordination in Support of National Priorities

This report describes the multiagency National Nanotechnology Initiative (NNI), which was established in FY 2001. The 15 agencies participating in this program have diverse missions, but each expects to derive benefits that support its mission and to advance national priorities through an increased basic understanding of nanoscale phenomena and the development of novel technologies.

Organization and Management

The NNI is an interagency effort aimed at maximizing the return on the Federal Government's investment in nanoscale R&D through coordination of funding, research, and infrastructure development activities at individual agencies. Ten of the Federal agencies participating in the Initiative have funding dedicated to nanotechnology R&D. Other Federal organizations perform related studies and research, apply technologies based on the results from those agencies performing nanoscale R&D, and participate in various NNI activities (See box below for lists of both sets of agencies).

In addition to sponsoring research, Federal support through the NNI provides crucial funds for the creation of university and government facilities with the specialized equipment and facilities required for nanoscale R&D. Federal support also helps educate the nanotechnology researchers of the future, as well as the workforce necessary for the growing use of nanotechnology in industry, primarily by providing funds for undergraduate, graduate, and postgraduate training in nanotechnology-related disciplines. The NNI plays a key role in fostering cross-disciplinary networks and partnerships, and in disseminating information to participating agencies and to the public, through workshops and meetings, as well as via the Internet (www.nano.gov). Finally, it encourages businesses, especially small businesses, to exploit the opportunities offered by nanotechnology.

Federal agencies with R&D budgets dedicated to nanotechnology research and development

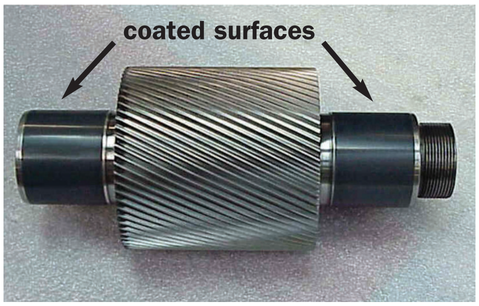
Department of Agriculture
Department of Commerce (in particular, the National Institute of Standards and Technology)
Department of Defense
Department of Energy
Department of Health and Human Services (in particular, the National Institutes of Health)
Department of Homeland Security (in particular, the Transportation Security Administration)
Department of Justice
Environmental Protection Agency
National Aeronautics and Space Administration
National Science Foundation

Other agencies participating in the NNI

Department of State
Department of Transportation
Department of Treasury
Food and Drug Administration
Intelligence Agencies

Nanotechnology on a Fast Track

The transition of nanotechnology research into manufactured products, while limited and preliminary, has already had significant impact. For example, a new form of carbon—the nanotube—was discovered in 1991. In 1995 it was recognized that carbon nanotubes were excellent sources of field-emitted electrons. By 2000, the "jumbotron lamp," a nanotube-based light source that uses these field-emitted electrons to bombard a phosphor, was already available as a commercial product. By contrast, the period of time between the modeling of the semiconducting property of germanium in 1931 and the first commercial product (the transistor radio) was 23 years.



Another example of rapid insertion of nanotechnology into useful applications is in the field of wear-resistant coatings. In the mid-1990s nanoceramic coatings exhibiting much higher toughness than conventional coatings were first developed. Beginning in 1996, the DOD supported partnerships among the Navy, academia, and industry to develop processes suitable for use in manufacturing and to evaluate the coatings for use in the marine environment. In 2000, the first nanostructured coating was qualified for use on gears of air-conditioning units for U.S. Navy ships; an example of such a gear is shown at left. In 2001, the technology was selected to receive an R&D100 Award. DOD estimates that use of the coatings on air valves will result in a $20 million reduction in maintenance costs over 10 years. The development of wear-resistant coatings by the DOD is clearly allied with its mission, yet will lead to commercial applications that can extend the lifetime of moving parts in everything from personal cars to heavy industrial machinery. (Photo above courtesy Robert Rigney, A&A Co.)

The NNI is managed within the framework of the National Science and Technology Council (NSTC). The NSTC is the principal means by which the President coordinates science and technology programs across the Federal Government, providing policy leadership and budget guidance. The NSTC's Subcommittee on Nanoscale Science, Engineering, and Technology (NSET) coordinates the plans, budgets, programs, and reviews for the NNI. The Subcommittee is composed of representatives from each participating agency, the Office of Science and Technology Policy, and the Office of Management and Budget.

The National Nanotechnology Coordinating Office (NNCO) serves as the secretariat to the NSET Subcommittee, and supports the Subcommittee in the preparation of multi-agency planning, budget, and assessment activities. To adequately support the growing NNI activities, the position of NNCO Director was changed from part-time to full-time in April 2003. The NNCO also serves as the point of contact on Federal nanotechnology activities for government organizations, academia, industry, professional societies, foreign organizations, and others. Finally, the NNCO develops and makes available printed and other communications materials concerning the NNI, and maintains the Initiative's website.

The Administration is focusing significant attention on the NNI. In order to further strengthen the Initiative, the President's Council of Advisors on Science and Technology (PCAST) has begun an external review of the NNI. The PCAST review will include a comprehensive assessment of the current NNI programs, and will lead to recommendations on how to improve the management of the program. PCAST's review of the Federal nanotechnology research program is an ongoing, long-term activity.

Funding Strategy

The NNI funding strategy is based on five modes of investment, each of which builds on previous and current nanotechnology programs.

The first investment mode supports a balanced investment in fundamental research across the entire breadth of science and engineering. Such fundamental research advances knowledge and understanding of novel physical, chemical, and biological properties of nanoscale materials and systems. This broad investment is critical because the outcome of basic research cannot always be anticipated, and discoveries in one discipline can have unexpected implications in another.

The second investment mode, collectively known as the "grand challenges," focuses on nine specific R&D areas that are more directly related to applications of nanotechnology and that have been identified as having the potential to realize significant economic, governmental, and societal impact.

The nine grand challenge areas are:

1. Nanostructured Materials by Design
2. Manufacturing at the Nanoscale
3. Chemical-Biological-Radiological-Explosive Detection and Protection
4. Nanoscale Instrumentation and Metrology
5. Nano-Electronics, -Photonics, and -Magnetics
6. Healthcare, Therapeutics, and Diagnostics
7. Efficient Energy Conversion and Storage
8. Microcraft and Robotics
9. Nanoscale Processes for Environmental Improvement

Research directed toward the grand challenge areas aims to efficiently and effectively accelerate the transition of scientific discovery into innovative technologies that show a return on investment as quickly as possible.

The third mode of investment supports centers of excellence that conduct research within the host institution(s). These centers pursue projects with broad multidisciplinary research goals that are not supported by more traditionally structured programs. These centers also promote education of future researchers and innovators, as well as training of a skilled technical workforce for the growing nanotechnology industry.

The fourth investment mode funds the development of infrastructure (e.g., the DOE user facility shown in Figure 2), instrumentation, standards, computational capabilities, and other research tools necessary for nanoscale R&D. The centers and infrastructure developed under the third and fourth modes facilitate the basic and applied research supported under the first two modes.

The fifth and final investment mode recognizes and funds research on the societal implications of nanotechnology, and addresses educational needs associated with the successful development of nanoscience and nanotechnology.

The FY 2004 Funding Request

As part of the FY 2004 Budget, President Bush requested $849 million for nanotechnology R&D across all of the agencies that participate in the NNI. This represents an increase of approximately 10% over the amount appropriated by Congress for FY 2003. Roughly two-thirds of the funding proposed under the NNI will support university-based research. Table 1 presents the nanotechnology R&D budget for FY 2002 through FY 2004 by agency.

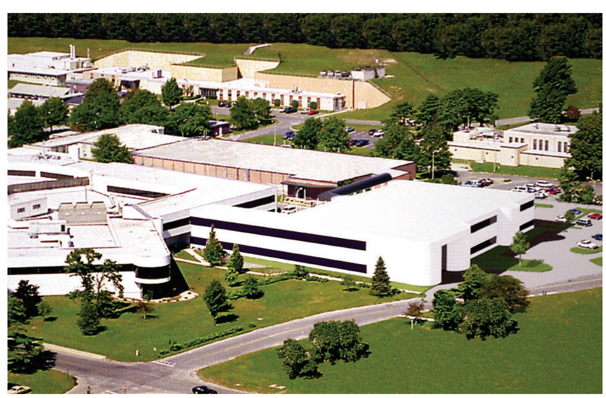


Figure 2. Conceptualization of the Center for Functional Nanomaterials, to be co-located with the National Synchrotron Light Source at the Department of Energy's Brookhaven National Laboratory.

Table 1. FY 2004 NNI Budget Overview by Agency
(Budget Authority, dollars in millions)

Agency	2002 Actual	2003 Request	2003 Appropriated*	2004 Request**	Change, 2003 to 2004†	% Change, 2003 to 2004†
NSF	204	221	221	249	28	13%
DOD	224	243	243	222	-21	-8%
DOE	89	133	133	197	64	48%
HHS (NIH)	59	65	65	70	5	8%
DOC (NIST)	77	69	66	62	-4	-6%
NASA	35	33	33	31	-2	-6%
USDA	0	1	1	10	9	900%
EPA	6	6	5	5	0	0%
DHS (TSA)#	2	2	2	2	0	0%
DOJ	1	1	1	1	0	0%
TOTAL	**697**	**774**	**770**	**849**	**79**	**10%**

*"2003 Appropriated" refers to planned outlays with appropriated dollars; actual FY 2003 outlays may vary.

**The total NNI request for FY 2004, as originally published in the President's FY 2004 Budget, was $792 million (see http://www.whitehouse.gov/omb/budget/fy2004/pdf/spec.pdf, p. 185). By the February Budget release, some agencies had identified additional items within their FY 2004 R&D budget requests as falling under the purview of the NNI. These updated figures are reflected in this table (see also http://www.ostp.gov/html/budget/2004/2004.html).

† Change between 2003 Appropriated and 2004 Request.

The NNI programs that are currently under DHS were under DOT prior to the formation of DHS in 2002.

Agency Abbreviations Used throughout this Report

DHS Department of Homeland Security
DOC Department of Commerce
DOD Department of Defense
DOE Department of Energy
DOJ Department of Justice
DOT Department of Transportation
EPA Environmental Protection Agency
HHS Health and Human Services
IA Intelligence Agencies
NASA National Aeronautics and Space Administration
NIH National Institutes of Health
NIST National Institute of Standards and Technology
NSF National Science Foundation
TSA Transportation Security Administration
USDA Department of Agriculture